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Influence of signal processing on sensitivity of the magnetoelastic torque sensor

***Abstract**. The paper presents the results of research on the influence of the signal processing on measurement sensitivity of the magnetoelastic torque sensor. The sensitivity of magnetoelastic element is already known, however it is not the only factor influencing the sensitivity of the sensor. Configuration of coils and type of excitation signal are also crucially important*

***Streszczenie.** W artykule przedstawiono wyniki badań wpływu przetwarzania sygnału na czułość pomiarową magnetosprężystego sensora momentu obrotowego. Czułość elementu magnetosprężystego jest już znana, jednak nie jest to jedyny czynnik wpływający na czułość sensora. Istotna jest także konfiguracja cewek i rodzaj sygnału wzbudzenia (**Wpływ przetwarzania sygnału na czułość czujnika momentu magneto-sprężystego**)*

Keywords: magnetoelastic sensors, torque sensors, amorphous materials.
Słowa kluczowe: sensor magnetosprężysty, sensor momentu skręcającego, materiały amorficzne.

Introduction

The latest research results on magnetoelastic torque sensors focus on the composite sensors where the magnetoelastic material is a layer glued to the support shaft. However, sensors based entirely on magnetoelastic materials, as in the proposed solution, are not being developed [1]. This is related to the lack of sufficient knowledge about the functional parameters of the proposed sensors, which are influenced also by the signal processing in these sensors.

The signal processing of the magnetoelastic torque sensor is relatively clear. Torque acts on the magnetic ring core of the sensor, introducing shear stress. The current flowing through the primary coil is magnetizing the core. For fixed magnetizing field produced by the coil, magnetic properties of the core, like magnetic flux density B and magnetic permeability μ, are affected by the applied stress. Changes of magnetic properties are detected as a change of signal in the sensing coil. The processing chain of the typical magnetoelastic torque sensor is shown in Fig. 1. Depending on the coils configuration, information about acting torque can be acquired by the measurement of either voltage or electric current [1,2].

Fig.1. Signal processing chain in the magnetoelastic torque sensor

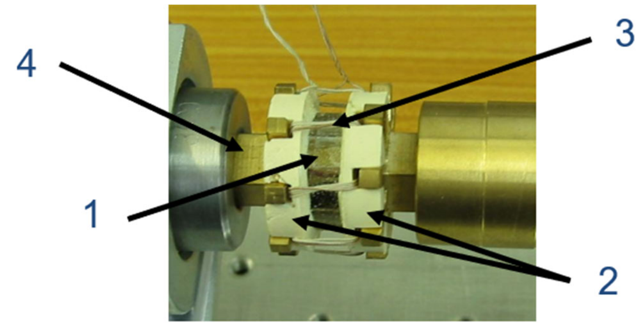

Fig.2. Magnetoelastic torque sensor with coils and torque transmission system: 1 – magnetoelastic sensing core, 2 – non-magnetic epoxy resin molds with protrusions for coils and torque transmission, 3 – magnetizing and sensing coils, 4 – clutches transmitting torque to the ring core.

The investigation was performed on the sensor in two possible coils configuration. The sensing element was a ferromagnetic ring core wound from an amorphous ribbon. The material of the ribbon was $Fe_{40}Ni_{38}Mo_4B_{18}$ soft magnetic alloy subjected to the thermal relaxation for 1 hour at temperature 380°C [5,6]. The relaxation was carried out in order to reduce post-production stress that arises in the ribbon during rapid quenching. After thermal relaxation, the ribbon was wound into the ring core and epoxy resin molds were made on the bases of the ring in order to stabilize the core [4]. Furthermore, the set of protrusions was formed on each mold allowing to wind the necessary coils and apply the torque by the specially designed clutch, as shown in Fig. 2.

Torque sensor configuration

Two configurations most often used in the operation of the magnetoelastic sensor were selected for the investigation. In the first one, known as the transformer configuration, the core is wound with two coils, where the primary one is the magnetizing coil and the secondary one is the sensing coil. In this configuration, the core is supplied with a sinusoidal current waveform of a fixed amplitude. Under the influence of magnetizing field and applied torque, the voltage waveform is induced in the sensing coil. Therefore, the torque is measured by the means of voltage signal. The configuration is presented in Fig 3

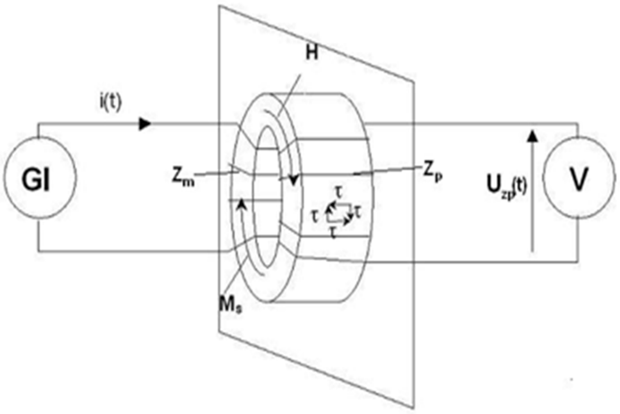

Fig. 3. Configuration of the magnetoelastic torque sensor with two coils and current supply – transformer configuration [3]

The second configuration includes only one coil. Due to the similarity with electronic choke, it can be called choke configuration. The core is supplied with an alternating sinusoidal voltage of fixed amplitude. Change of the magnetic permeability under the operation of applied torque influences inductance of the coil and therefore affects the current flowing in the circuit. The current measurement is carried out by measurement of the voltage drop across the resistor connected in series with the sensor coil, allowing to obtain voltage signal most suitable for further processing. The configuration is shown in Fig 4.

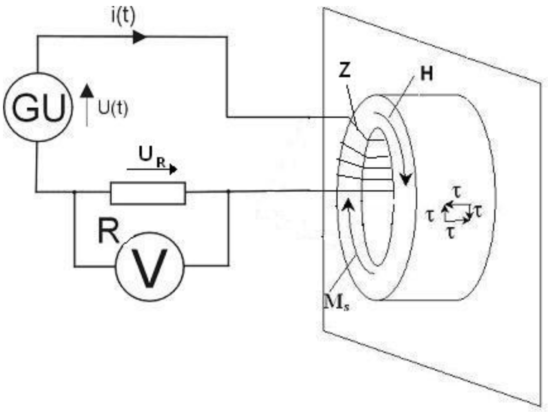

Fig. 4. Configuration of magnetoelastic torque sensor with one coil and voltage supply – choke configuration [3].

The purpose of the following paper is to investigate influence of both configurations on the sensitivity of the sensor. Measurements were performed with specially designed mechanical setup allowing step increasing the torque applied to the sensor core. The characteristics of sensor in both configurations were determined on the basis of obtained results and sensitivities were calculated allowing to compare the presented solutions of signal processing.

For the voltage measurement, FLUKE 8846A precise multimeter was used with a measurement accuracy of 0.03%. The voltage drop in choke configuration was measured across the 10-Ohm reference resistor with 0.01% accuracy. The signal generator SIGLENT SDG1010 with output voltage accuracy of 3% was used as a source of excitation signals. The torque measurement was performed with the accuracy of 1%.

Results of the research

As a result of the investigation, the following results were obtained. For the sensor in the transformer configuration, the several series of measurements were performed for torque M_s values from 0 Nm to 4.2 Nm. Each series was measured for fixed value of the magnetizing field amplitude. The values of the applied magnetizing field depended on the multiplicity of the coercive field H_c within the multiplier range from 1 to 5. Higher amplitudes of the magnetizing field were rejected due to a significant decrease in the sensor sensitivity, as material is approaching magnetic saturation. On the other hand, the lower amplitudes were rejected due to a significant increase of measurement uncertainty resulting from low measurement signal value and therefore low signal to noise ratio SNR. The output signal was voltage induced in the sensing coil. The measured output signal parameters were RMS value U_{RMS} and the peak-to-peak value U_{p-p}. Fig. 5 presents the measurement results for the peak-to-peak voltage U_{p-p}.

In the transformer configuration, the results obtained for peak-to-peak values U_{p-p} exhibited high measurement sensitivity. However, the important disadvantage of the torque measurement through U_{p-p} value in this configuration was high measurement uncertainty of the obtained results.

Fig. 6. shows the measurement results for the RMS voltage U_{RMS} of the sensor in the transformer configuration.

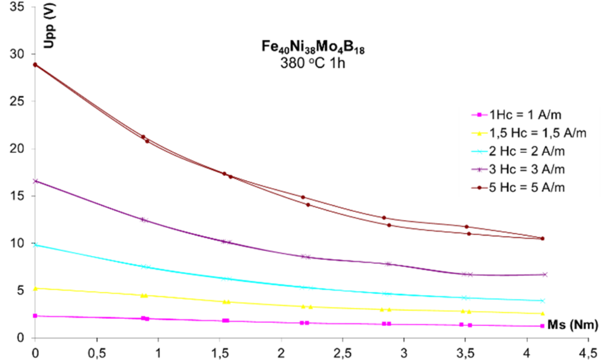

Fig. 5. Characteristics of the magnetoelastic torque sensor with peak-to-peak signal measurement in the transformer configuration

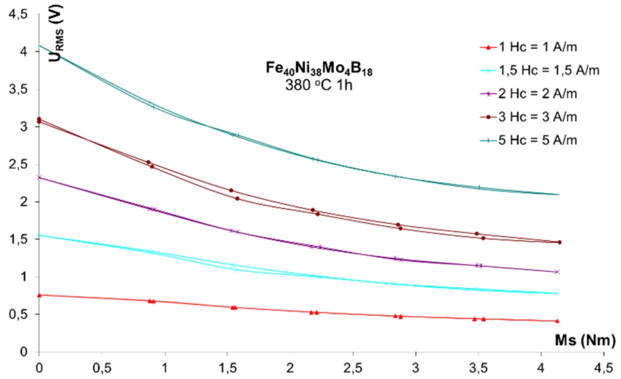

Fig. 6. Characteristics of the magnetoelastic torque sensor with RMS signal measurement in the transformer configuration [3]

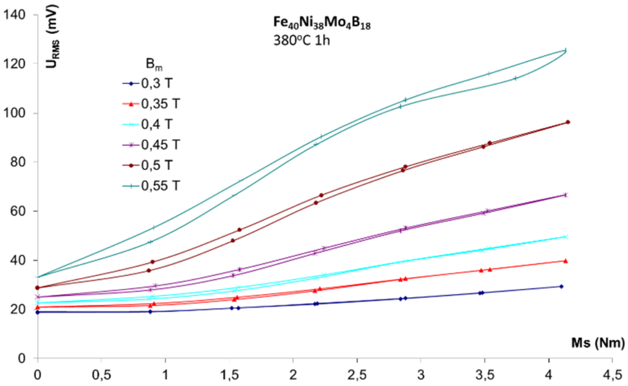

Fig. 7. Characteristics of the magnetoelastic torque sensor with RMS signal measurement in the choke configuration [3]

The results obtained in this configuration for RMS measurement were also exhibiting high sensitivity, however the measurement uncertainty was much lower than in previous case.

For the sensor in the choke configuration, the several measurement series were performed in a similar way for torque M_s with values from 0 Nm to 4.2 Nm. The series were measured for the fixed amplitudes of magnetic flux density B_m. The values of flux density were selected in such a way that the magnetizing field amplitude H_m corresponding to the expected B_m of the unloaded sensor was the same as in the transformer configuration. The measurement series with the highest sensitivity were also determined for this configuration.

The output current signal was measured by the means of voltage drop across the measurement resistor connected in series with the coil. Again, the RMS value U_{RMS} and the peak-to-peak value U_{p-p} were measured. However, the measurement results for the peak-to-peak value were subjected to relatively high uncertainty. Fig. 7 presents the measurement results for the RMS voltage U_{RMS} for the sensor in a choke configuration.

In the choke configuration, when measuring the output signal by the means of RMS voltage U_{RMS}, an exceptionally high measurement sensitivity exceeding 300% was obtained. A slight measurement hysteresis was observed for higher values of magnetic flux density B_m. However, this drawback is compensated by high sensitivity.

In the presented work, the absolute sensitivity S_U and relative sensitivity S_{U2} were calculated for U_{RMS} measurement in both configurations, according to the following formulas:

$$S_U = \frac{\Delta U_{RMS}}{\Delta M_S} \tag{1}$$

$$S_{U2} = \frac{\frac{\Delta U_{RMS}}{U_{RMS0}}}{\Delta M_S} = \frac{S_U}{U_{RMS0}} \tag{2}$$

where U_{RMS0} is RMS voltage measured of unloaded sensor. For the transformer configuration, the sensitivities were calculated for the results obtained at magnetizing filed of 5 A/m ($5H_c$), while the magnetic flux density in choke configuration was 0.55 T. The calculated results are presented in Table 1. The comparison of both configurations can be performed on the basis of relative sensitivity S_{U2}. Presented results clearly indicate, that for choke configuration, the relative sensitivity is almost two times higher than in transformer configuration.

Table 1. Absolute sensitivity S_U and relative sensitivity S_{U2} of investigated magnetoelastic torque sensor in transformer and choke configuration.

Configuration	Absolute sensitivity S_U (mV/Nm)	Relative sensitivity S_{U2} (1/Nm)
Transformer	471.0	0.10
Choke	24.1	0.18

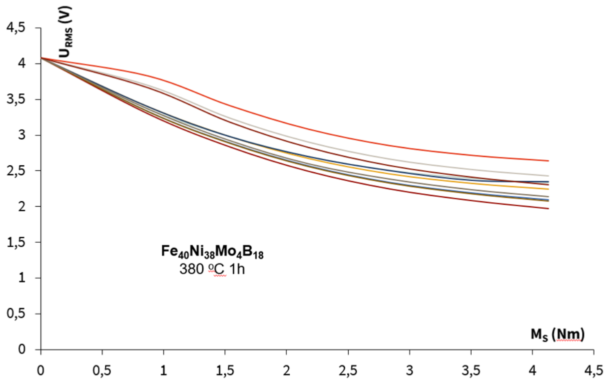

Fig. 8. Magnetoelastic measurement characteristics of the torque sensor in transformer configuration, ten series of U_{RMS} measurement

Both sensor configurations were also investigated in terms of measurement uncertainty. Ten measurement series within the torque range from 0 Nm to 4.2 Nm were performed consecutively in each configuration. The obtained results for both sensor configurations are presented in Fig. 8 and Fig. 9. The measurement for transformer configuration was performed at the same conditions, as in the sensitivity calculation – the magnetizing field value was 5 A/m and the magnetic flux density was 0.55 T. In both cases the RMS value U_{RMS} of the output signal was measured.

As can be seen in Fig. 8 and Fig. 9, the standard deviation of indications in the specific point is much lower for the choke configuration. It is especially highlighted by the variation bars representing the range of changes of measurement results at certain point in all ten performed measurement series. The variation bars along with average characteristic are presented for sensor in both transformer configuration and choke configuration in Fig. 10 and Fig. 11 respectively.

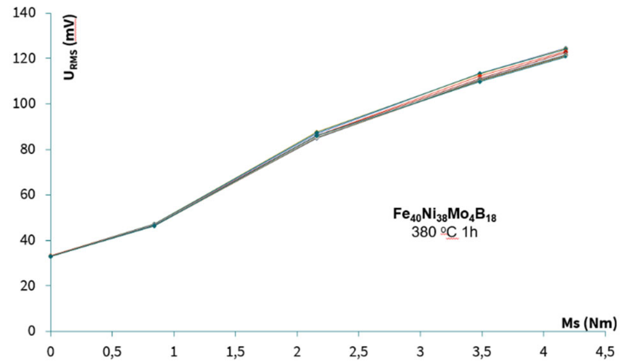

Fig. 9. Magnetoelastic measurement characteristics of the torque sensor in choke configuration, ten series of U_{RMS} measurement

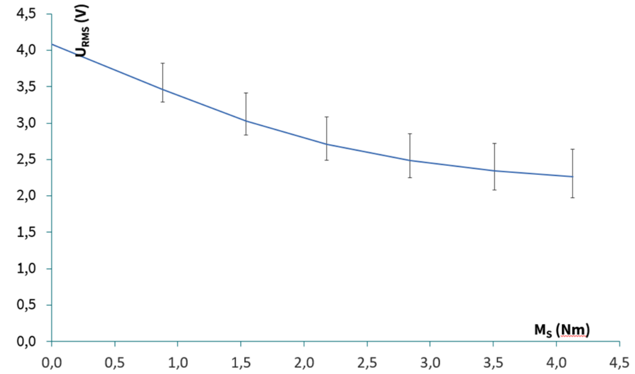

Fig. 10. The average characteristic and variation bars at individual points for magnetoelastic torque sensor in transformer configuration

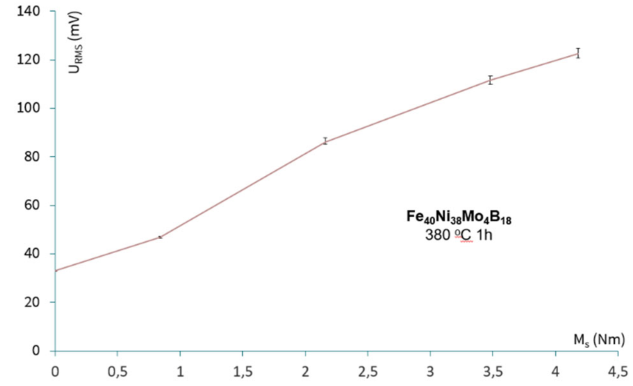

Fig. 11. The average characteristic and variation bars at individual points for magnetoelastic torque sensor in choke configuration

Conclusion

The performed investigation and analysis indicate that the magnetoelastic torque sensor in the choke configuration exhibits significantly better measurement parameters than in case of transformer configuration. The choke configuration is characterized by significantly higher relative change of output signal of approximately 300% while for the transformer configuration the relative change reaches approximately 55%. Moreover the measurement uncertainty in case of the choke configuration exhibits much lower values, indicating higher precision of the sensor in this configuration. One of the reasons for the higher result variation in transformer configuration may be the need of using two coils.

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